National Aeronautics and
Space Administration

Mars Sample Return Capability Development: Mars Ascent Vehicle and Mars On-Orbit Rendezvous

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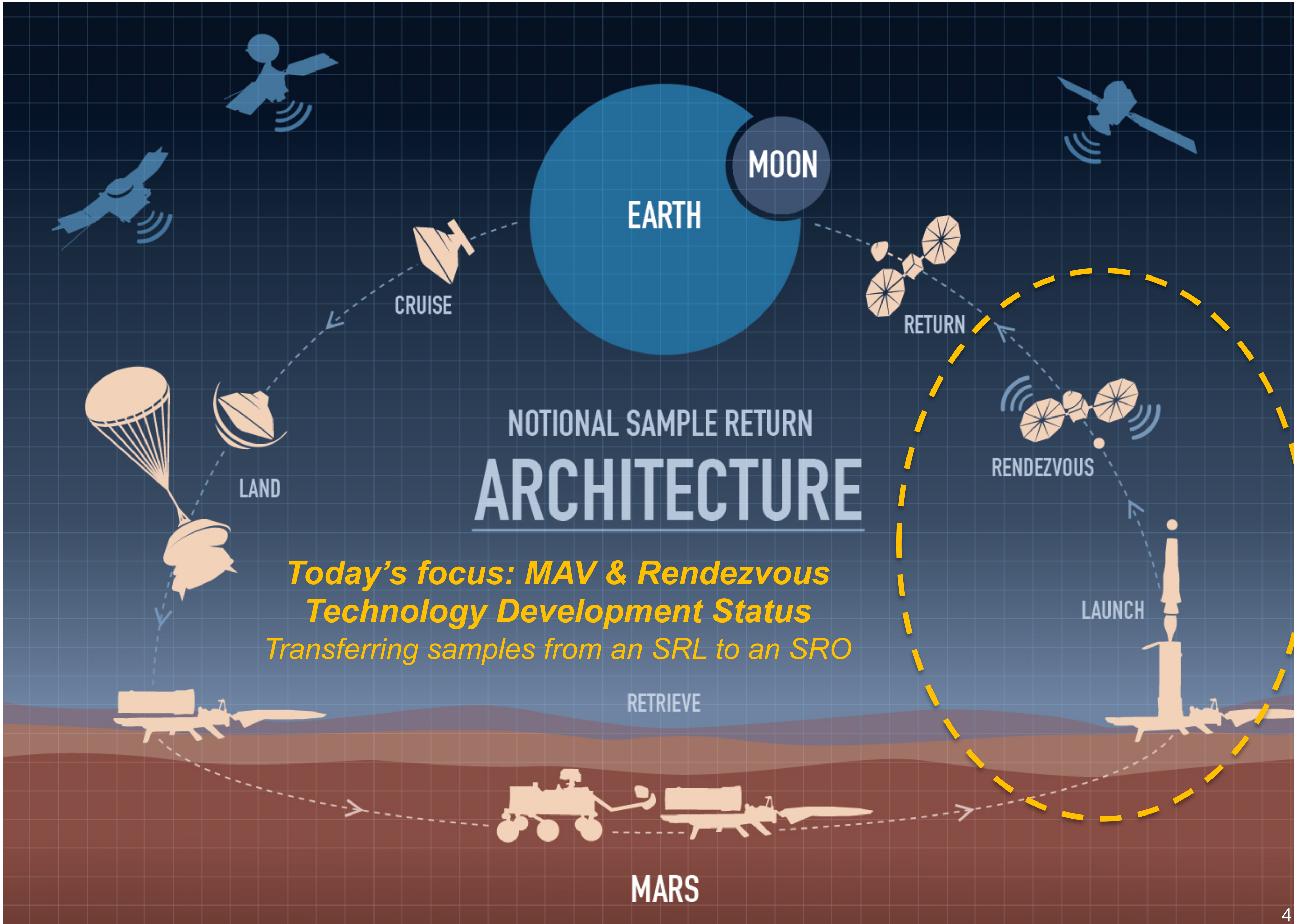
Executive Summary

- Mars Ascent Vehicle and Rendezvous are key capabilities that would be needed for Mars Sample Return
  - A Sample Retrieval Lander's MAV would launch an Orbiting Sample (containing collected samples) into stable Mars orbit
  - A Sample Return Orbiter would perform on-orbit Rendezvous w/ OS for Earth return
- Focused technology developments have advanced the maturity of the MAV and Rendezvous capabilities
- Future developments would establish readiness for SRL/SRO launch as early as 2026

Outline

- Notional MSR Campaign Overview
- Capability Development Status
  - Mars Ascent Vehicle
  - Orbiting Sample
    - Fundamental interface between an SRL and an SRO
  - Mars On-orbit Rendezvous concept
- Summary



Today's focus: MAV & Rendezvous Technology Development Status

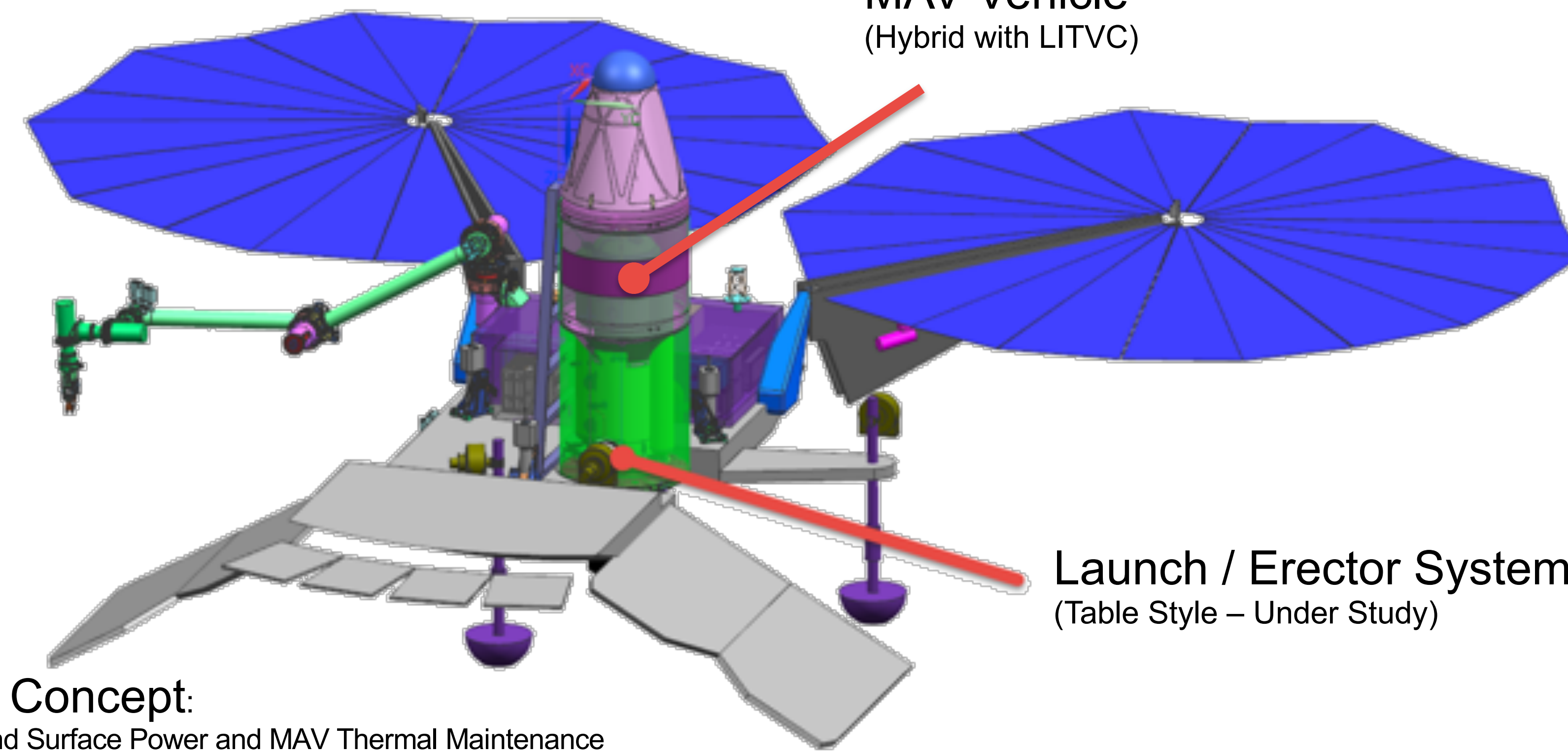
Transferring samples from an SRL to an SRO

MAV Technology Development

MAV Concept Overview

Driving MAV Requirements:

- ~300-400 km, “due east” circular orbit
- 12 kg Orbital Sample Canister Payload
- Launch from potential M2020 Landing Sites
- 9 months surface survivability with SRL support
- Cold (-20ºC) Operational temperature



Lander Concept:

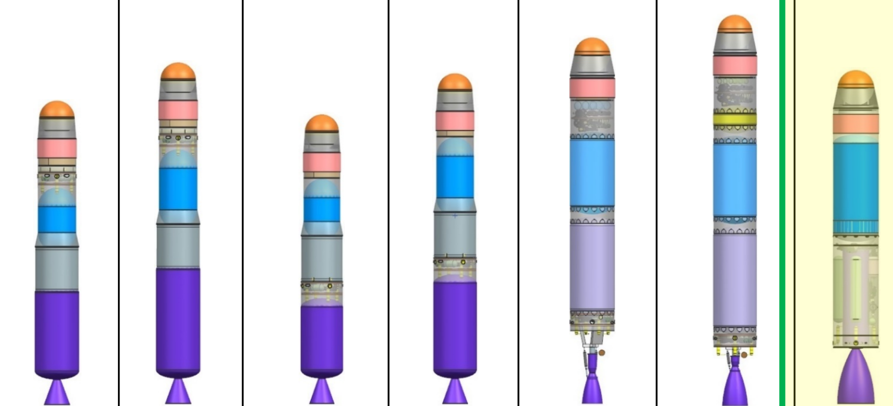
- Cruise and Surface Power and MAV Thermal Maintenance
- Launch Tube with Thermal Insulation to Minimize Energy Costs
- MAV Navigation Initialization
- Erector and Initial Launch Stability

Mars Ascent Vehicle 2015 Case Studies

- JPL/MSFC/LaRC carried out trade study in FY15 of MAV implementation options
  - Solid-Solid two-stage
  - Liquid bi-prop SSTO
  - Hybrid SSTO
- Based on propulsion performance and thermal accommodation, Hybrid SSTO option selected as current focus

2015 MAV Architecture Study

	Case 1a	Case 1b	Case 2a	Case 2b	Case 5	Case 6	Case 7
	Solid-Solid G-G	Fixed Solid-Solid G-G	Solid-Solid G-U	Fixed Solid-Solid G-U	SSTO Pump BiProp	SSTO Reg. BiProp	SSTO Hybrid
GLOM:	319 kg	342 kg	274 kg	297 kg	255 kg	270 kg	219 kg
Length:	2.64 m	2.96 m	2.51 m	2.87 m	3.21 m	3.39 m	2.89 m
AFT:	-58 C	-58 C	-58 C	-58 C	-90/-44 C	-90/-44 C	-90/-66 C



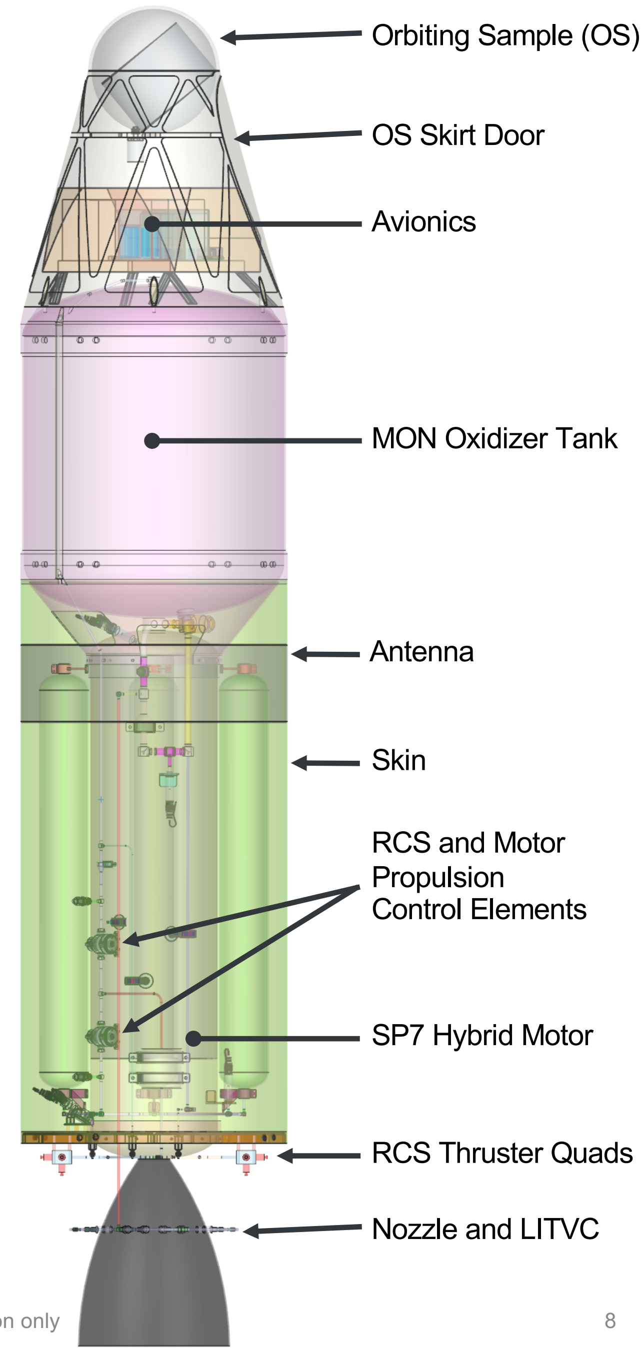
GLOM: Gross Liftoff Mass (CBE values shown)
AFT: Allowable Flight Temperature
SSTO: Single Stage to Orbit

Broad study of MAV architectures has led to the current Hybrid SSTO approach

MAV Reference Design

- Continued Study from 2015…
  - Added Subsystem Maturity and Fidelity
  - Validated Single-Stage-To-Orbit Design
    - Target Orbit 350 km @ 18º Inclination
    - 12 kg OS Capability (31-Tubes)
  - Length: 2.4 m x Diameter: 0.57 m
  - GLOM Range: 290-305 kg (w/ 50% margin)
    - Varies with launch uncertainties
  - Mass Fractions
    - Propulsion Dry Mass : 10%
    - Non-propulsion Dry Mass : 12%
    - Oxidizer Mass: 63%
    - Fuel Core Mass: 14%
    - Helium Mass: <1%

GLOM	Gross Liftoff Mass
LITVC	Liquid Injection Thrust Vector Control
OS	Orbiting Sample
RCS	Reaction Control System
TPS	Thermal Protection System



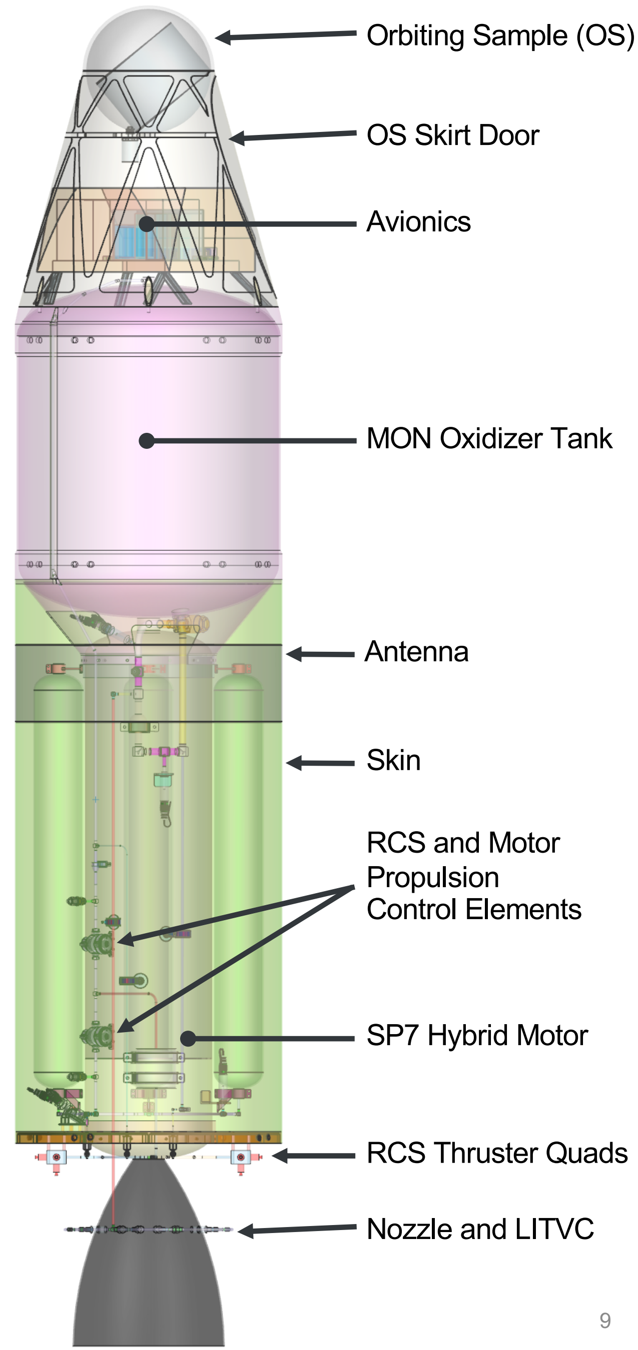
Hybrid MAV Technical Maturity

Subsystem	Maturity
OS	Significant Early Work and Prototyping Completed
Nose & Structure	Standard Flight Engineering
Avionics	Standard Engineering, Based on Europa Lander
Prop Tanks	Standard Flight Tank Engineering
Prop Components	Valves and Regulators are Long Lead Developments
Hybrid Motor	Technology Development Underway
RCS Components	Standard Engineering
LITVC	Technology Development Underway

High Maturity

Advanced Engineering

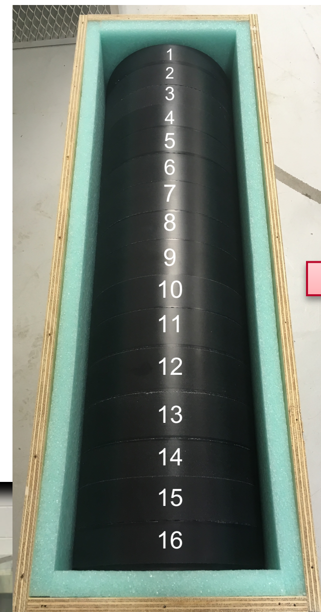
Technology Development

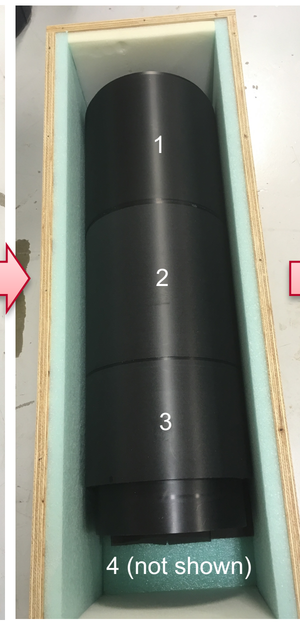


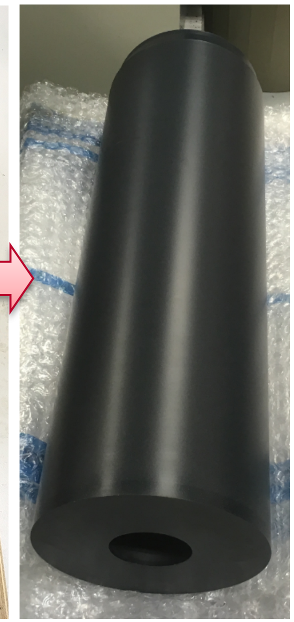
GLOM	Gross Liftoff Mass
LITVC	Liquid Injection Thrust Vector Control
OS	Orbiting Sample
RCS	Reaction Control System
TPS	Thermal Protection System

MSFC SP7 Fuel Grain Work

- MSFC has developed a robust and repeatable fuel grain manufacturing technique
  - Started making grain in many segments
  - Now capable of full-scale monolithic grains

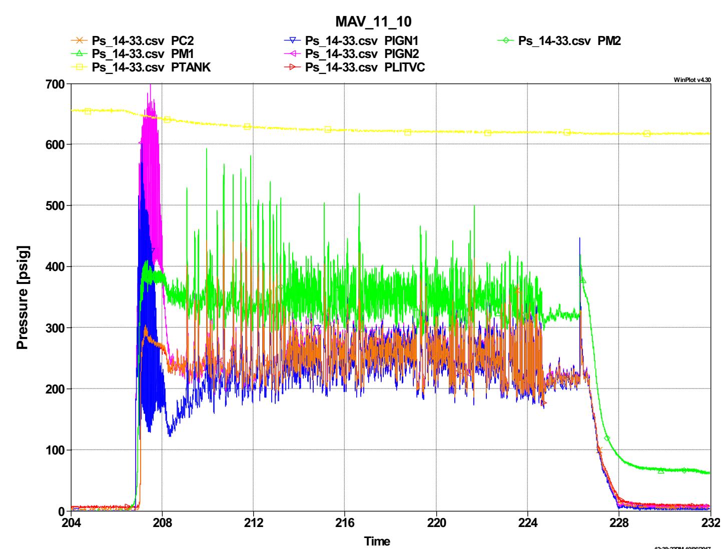






MAV Testing Progress - SPG

Complete **Oct 5 & 13, 2017**	✓ Motor 1: Verify ignition of desired propellant combination at scale. ✓ Motor 2: Extend burn duration (>20 s) and work on stability
November 2017 (in progress)	Motor 3: Burn fuel grain to completion, restart at similar conditions to 2[nd] burn on MAV, extend burn durations, reduce insulation mass
December 2017	Motor 4: LITVC demonstration Motor 5: Burn fuel grain to completion, extend burn durations
January 2018	Motor 6: Full duration burn with a restart (motor inspection between burn 1 and 2) Motor 7: Full duration burn with a restart (no outside intervention)



MAV Testing Progress – Whittinghill

Complete

✓ Heavy Weight Motor 1 (two burns):
- Smooth and rapid ignition
- Establish SP-7 regression rate at full scale
- Demonstrate smooth combustion
- Demonstrate high c* efficiency
- Obtain initial LITVC data

November 2017 (in progress)

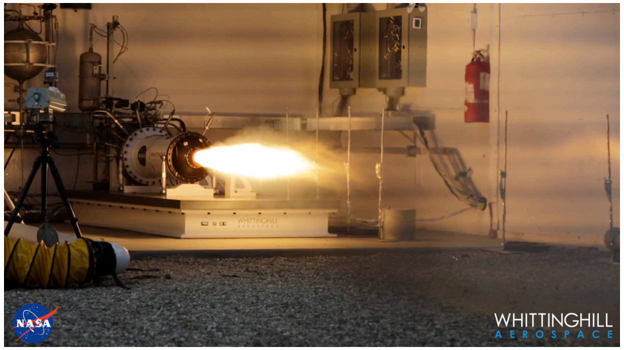
Heavy Weight Motor 2:
- Burn motor on peak O/F
- Increase burn time (~60 sec)
- Demonstrate high c* efficiency with minimal system impact
- Investigate alternate injector patterns for more benign fuel impingement effects
- Continue acquiring LITVC data

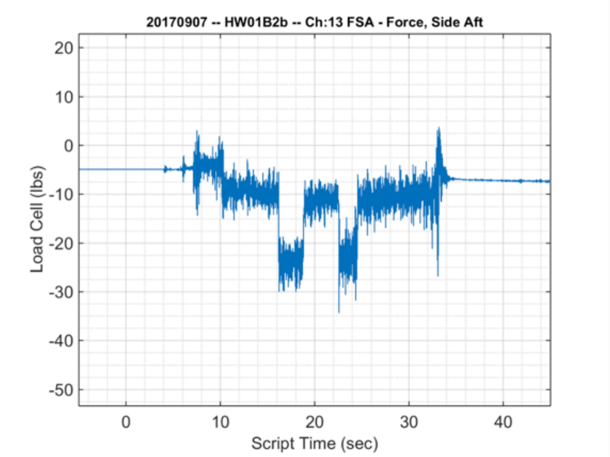
December 2017

Flight Type Motor 3:
- Investigate lower injector deltaP for (flight) He conservation
- One burn, near full duration
- Continued LITVC

January 2018

Flight Type Motor 4:
- Full impulse for MAV mission
- C* efficiency > 0.95
- High Fuel utilization
- Remote re-start, 2 burns on a MAV mission profile.
- Continued LITVC





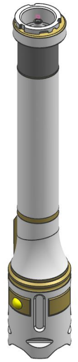
MAV Technology Development Status

OS Concept

Orbiting Sample (OS) Concept Overview

- The OS provides a container to securely hold and protect the M2020 Sample Tubes (nominally 31) for return to Earth
  - Mars atmospheric samples are also contained in the OS and returned to Earth
- Orbital Sample (OS) interfaces directly with both SRL/MAV and SRO elements of MSR
- The OS with Sample Tubes must withstand environments imposed by SRL, SRO, EEV

Current OS Reference Design

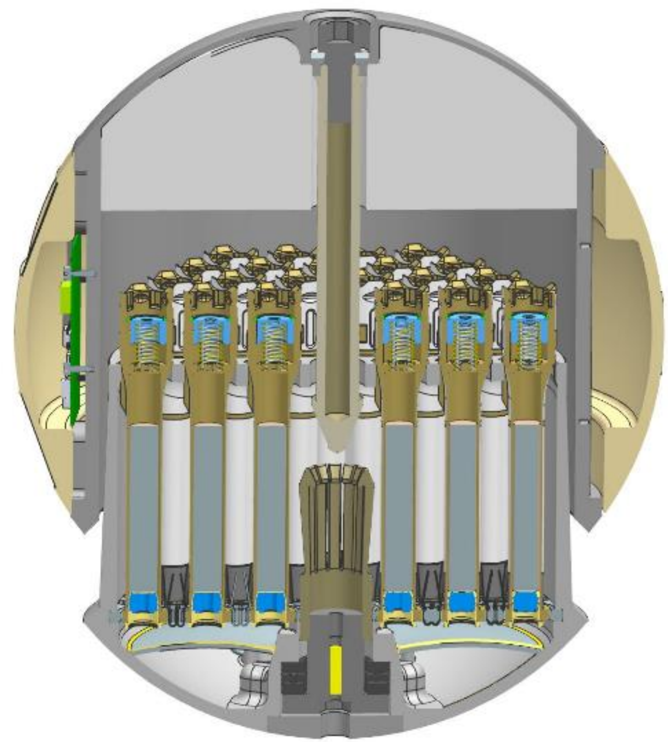


Mars 2020 Sample Tube Assembly

Engineering OS ready for impact testing

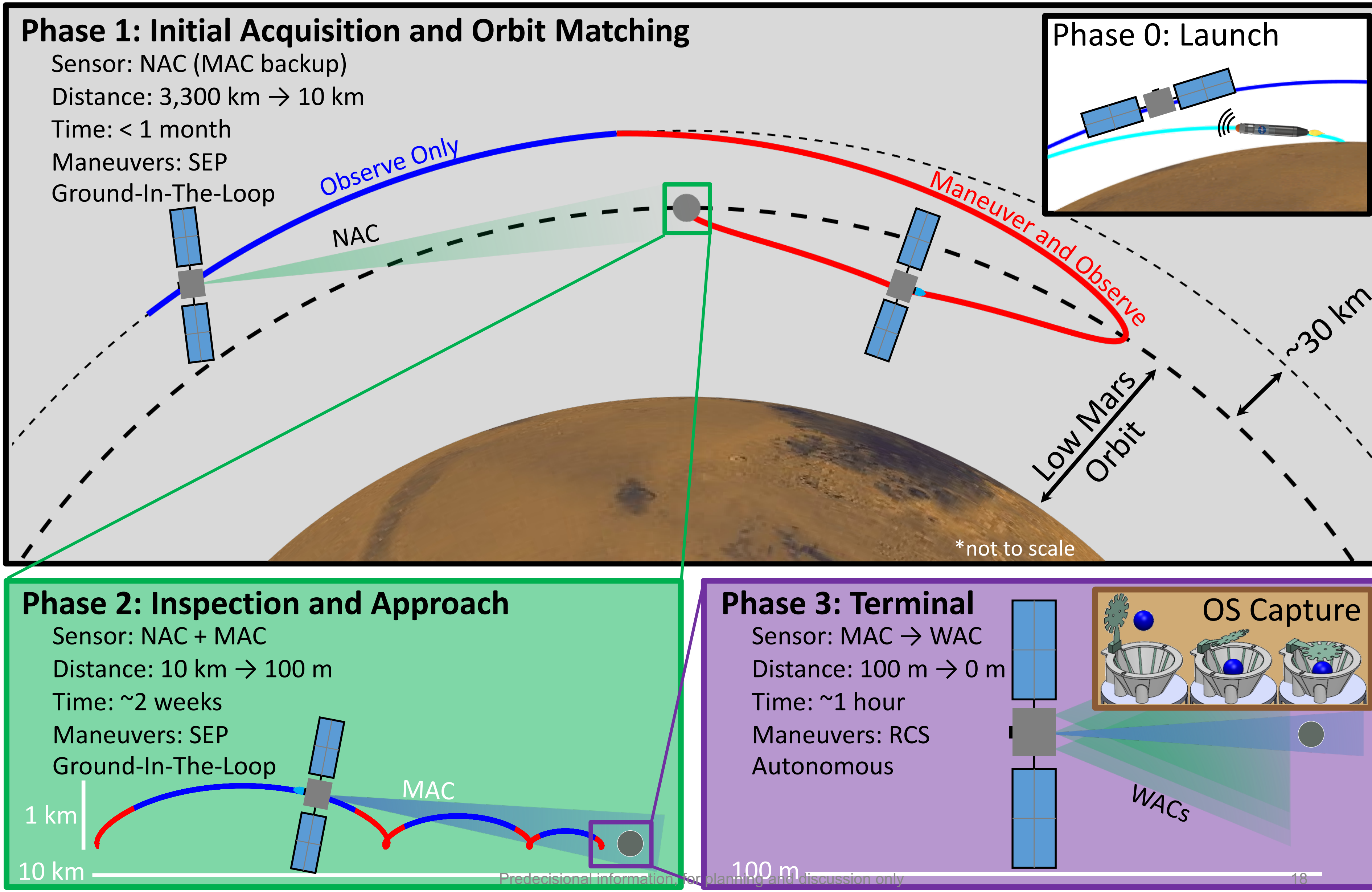
OS Architecture and Design Approach

- OS Concept
  - 31 tube slots, central rod for load support
  - 2 air sample tanks with manual valves
  - Assembled at Mars with aluminum foam to provide tube preload for EEV landing
- Surface
  - Sandblasted gold meets thermal, albedo, & specular reflectance requirements
- Mass & diameter
  - Mass ≤ 12 kg
  - Diameter ≤ 28 cm



Rendezvous Concept

Rendezvous Concept Overview



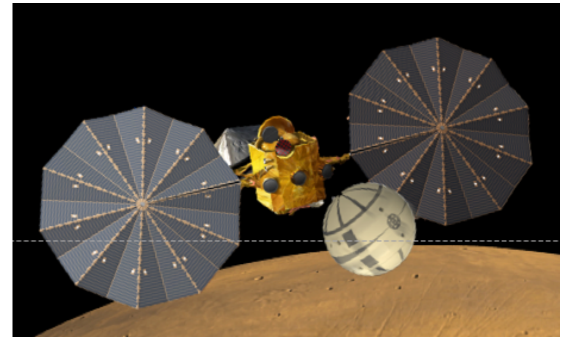
Rendezvous Concepts: MSR vs Earth-Orbit (e.g., ISS)

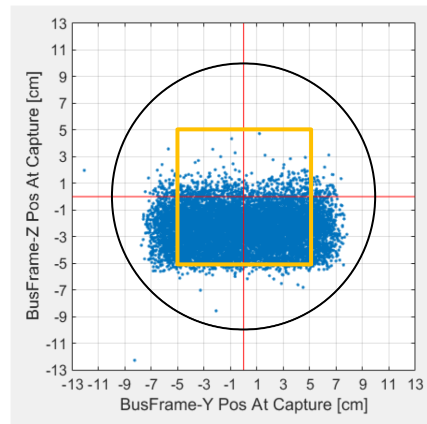
<table>
<tr><th></th><th>Long Range (>10 km)</th><th>Medium Range (10 km - 100 m)</th><th>Short Range (<100 m)</th><th></th></tr>
<tr><td rowspan="6">MSR Harder than ISS</td><td>Significant MAV Delivery Errors</td><td></td><td></td><td>Increases propellant required</td></tr>
<tr><td colspan="2">OS harder to image than ISS (smaller, farther from sun)</td><td></td><td rowspan="4">Long range optical detection required</td></tr>
<tr><td colspan="2">No GPS Available</td><td></td></tr>
<tr><td colspan="2">No Ground Tracking</td><td></td></tr>
<tr><td colspan="3">Target is passive</td></tr>
<tr><td></td><td colspan="2">Round Trip Light Time ≈ Minutes</td><td>Increased autonomy required</td></tr>
<tr><td rowspan="6">MSR Easier than ISS</td><td colspan="2">Orbit matching is allowed to take weeks</td><td></td><td>Reduces propellant and autonomy requirements</td></tr>
<tr><td colspan="3">Target shape is simple (sphere)</td><td rowspan="3">Complicated LIDAR/image processing not needed</td></tr>
<tr><td colspan="3">Target surface properties known and can be tailored to rendezvous</td></tr>
<tr><td></td><td></td><td>Relative Attitude does not need to be controlled</td></tr>
<tr><td></td><td></td><td>Unconstrained approach vector</td><td rowspan="2">Safer and more straightforward rendezvous strategy</td></tr>
<tr><td></td><td></td><td>Abort options are less constrained</td></tr>
</table>

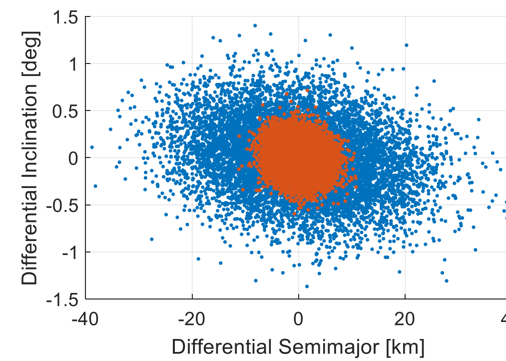
- Many commercial and international partners have experience with rendezvous at the ISS
- The main new challenges for a potential MSR:
  - Long range acquisition of the OS (this is done by GPS and ground sensing for ISS)
  - Completely autonomous terminal phase (round trip light time too high for human-in-the-loop)
- However, many aspects are easier:
  - Because the OS is a sphere, its attitude is not relevant for rendezvous
  - Because the OS is small, there are no “keep-out corridors” complicating the approach and abort vectors

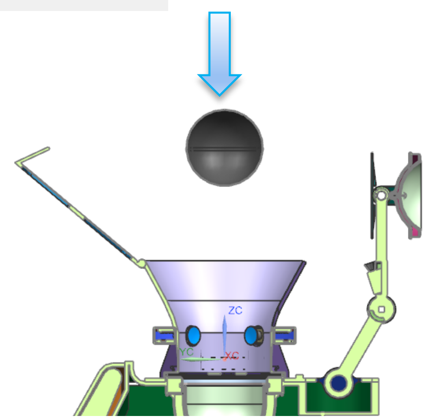
Driving Rendezvous Requirements

- OS:
  - Diffuse Sphere
  - Diameter = 28cm
  - Albedo: ≥ 0.3
- MAV Orbit:
  - Low Mars Orbit, circular
  - Unconstrained beta angle
  - Inclination: ±1° (3σ)
  - Semimajor axis: ±32 km (3σ)
- Capture Vector (3σ):
  - Position: ± 10 cm
  - Velocity: 5 ± 1 cm/s
  - Direction: ± 5°
- System Considerations:
  - Remain fail-safe until terminal phase
  - Single-Fault Tolerance





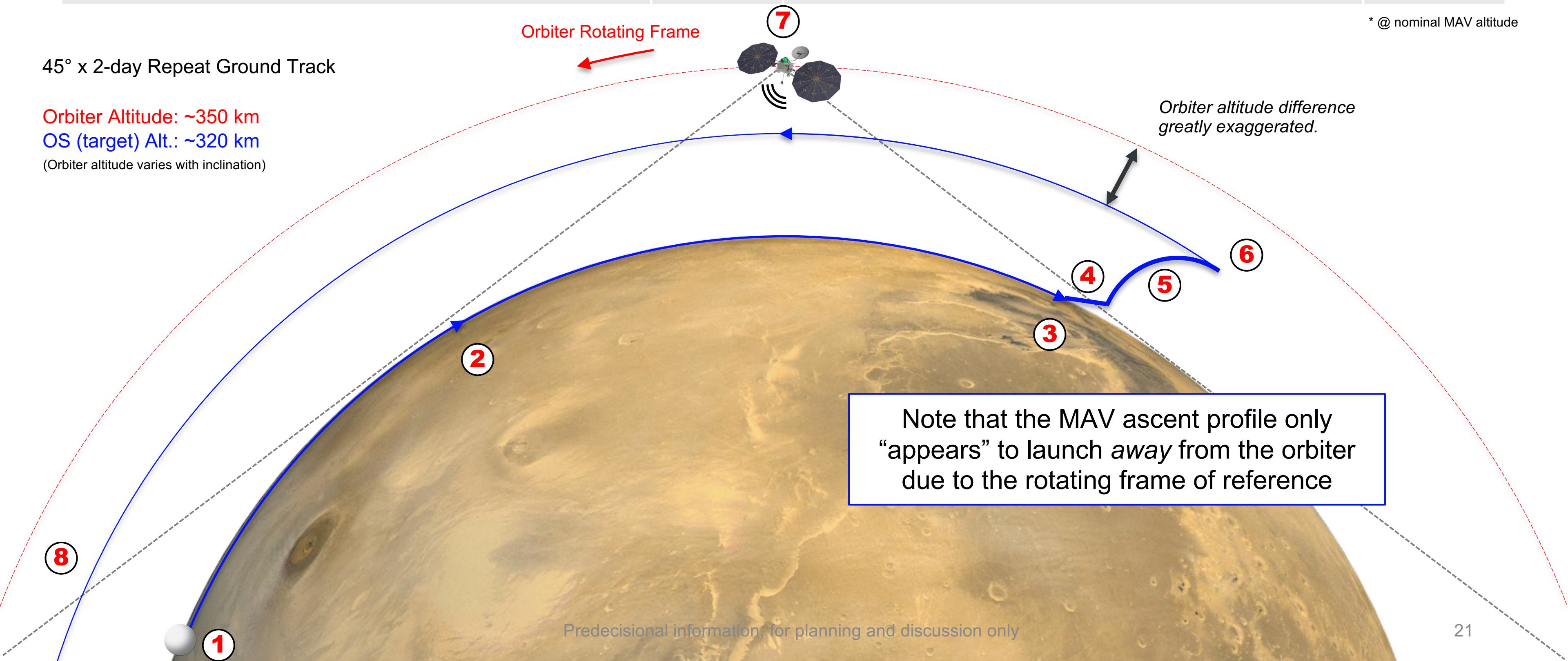




Notional MAV Launch Sequence

Event	Time	Event	Time
1 MAV Ready for Launch	L-2d	5 Ascent Coast Phase	L+15m
2 MAV-Orbiter In-View (Go / No Go)	L-20m	6 2nd Burn / OS Separation	L+16m
3 MAV Launch	L-0	7 OS Passes under Orbiter	L+15h*
4 Ascent 1st Burn	L+2m	8 OS Occulted by Mars	L+39h*

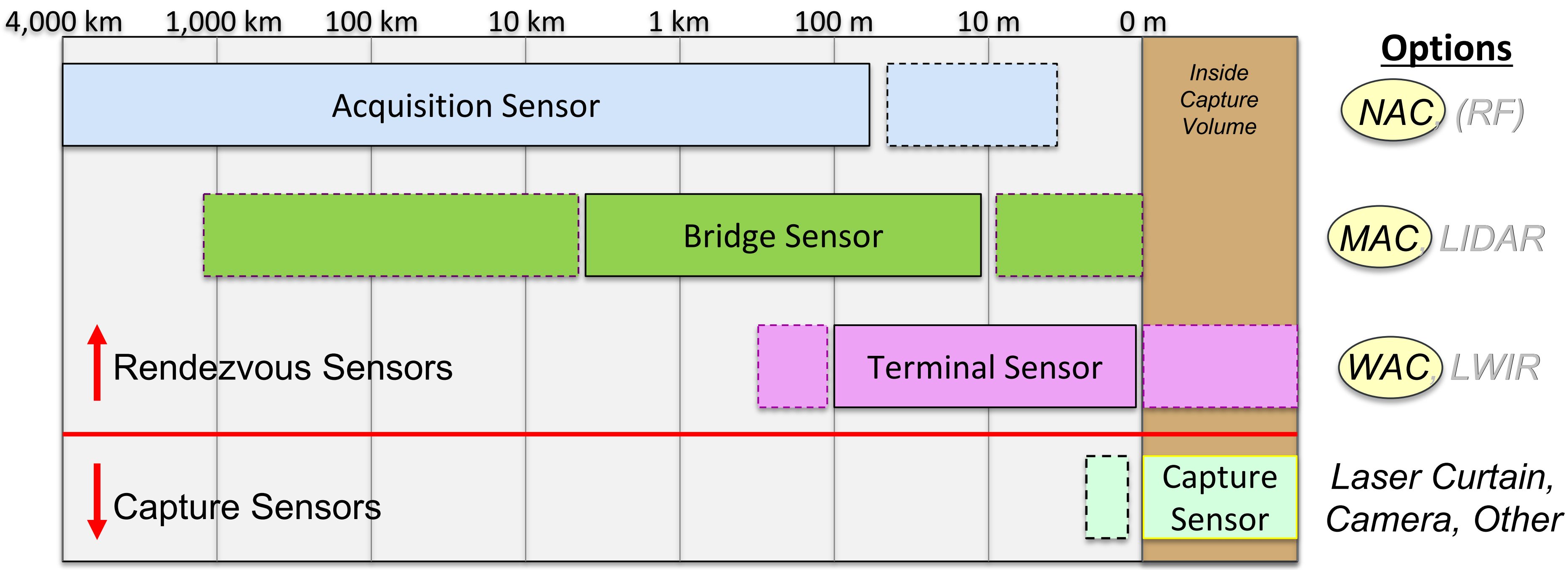
* @ nominal MAV altitude



Note that the MAV ascent profile only "appears" to launch *away* from the orbiter due to the rotating frame of reference

Predecisional information; for planning and discussion only

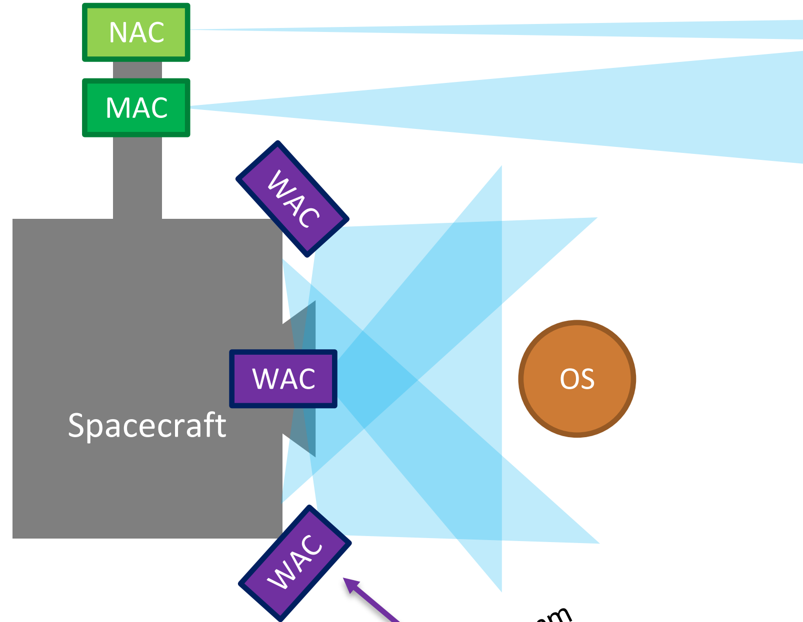
Rendezvous Sensor Domains

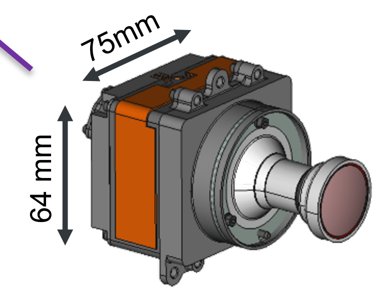


Sensor	Max Range	Min Range	FOV	Aperture	Detector	Accuracy	Phase Angle
NAC Narrow Angle Camera	>3,500 km	10 – 50 m	5° – 8°	5 – 10 cm	Existing	<35 μrad	< 90°
MAC Medium Angle Camera	>1,000 km	1 – 10 m	10° – 60°	3 – 5 cm	Existing	<500 μrad	< 90°
LIDAR	1 – 10 km	1 – 10 m	~20°	~5 cm	Existing	~3 mrad Range: ~10 cm	All
WAC Wide Angle Camera	100 m – 1 km	0 – 1 m	60° – 120°	1 – 5 cm	Existing	~1 mrad	< 90°
LWIR Long Wave Infrared	200 m – 2 km	0 – 1 m	60° – 120°	2 – 5 cm	Existing	~3 mrad	All

Reference Sensor Suite

- **Narrow Angle Camera**
  - Provides initial detection of OS at max. range (~3,500 km)
- **Medium Angle Camera**
  - Maintains visual lock during approach, provides relative navigation information
  - Can detect OS at long range (>1,000 km) in case NAC fails
- **Wide Angle Cameras**
  - Stereoscopic view of the OS at terminal approach, and covers a wide swatch of sky to provide situational awareness





Mars2020 EECAM

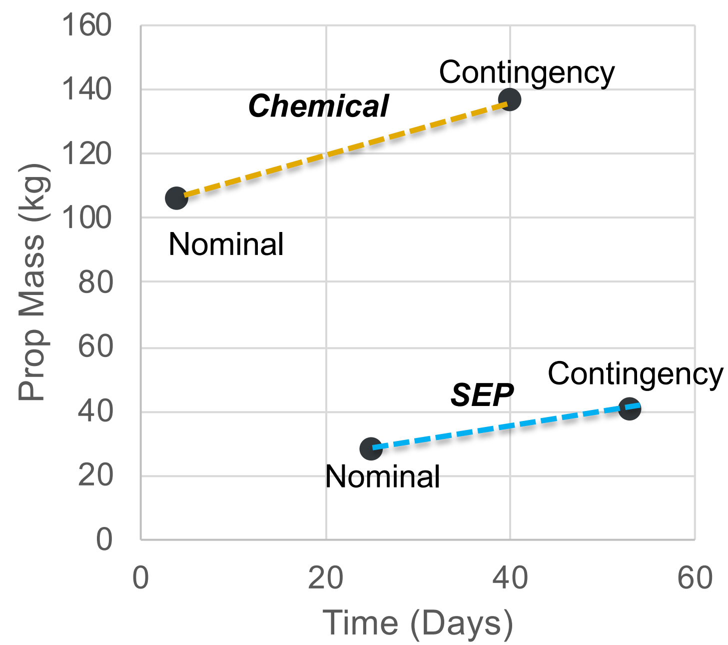
<u>Example Hardware:</u>
- WAC = M2020 EECAM Build-to-Print
- NAC and MAC use EECAM detector and electronics, but with larger optics
- All 5 cameras: ~10kg, 15W

SEP vs Chemical Orbit Matching

		3σ Values Nominal Ops			3σ Values Contigency Ops		
Propulsion Option	Isp [sec]	Time [days]	Delta V [m/s]	Propellant [kg]	Time [days]	Delta V [m/s]	Propellant [kg]
Chemical	230	4	78	106	40	100	136
SEP	2600	25	233	28	53	341	40

(Contingency scenario corresponds to failure to detect OS prior to first occulation, requiring 10-day limb-scanning period)

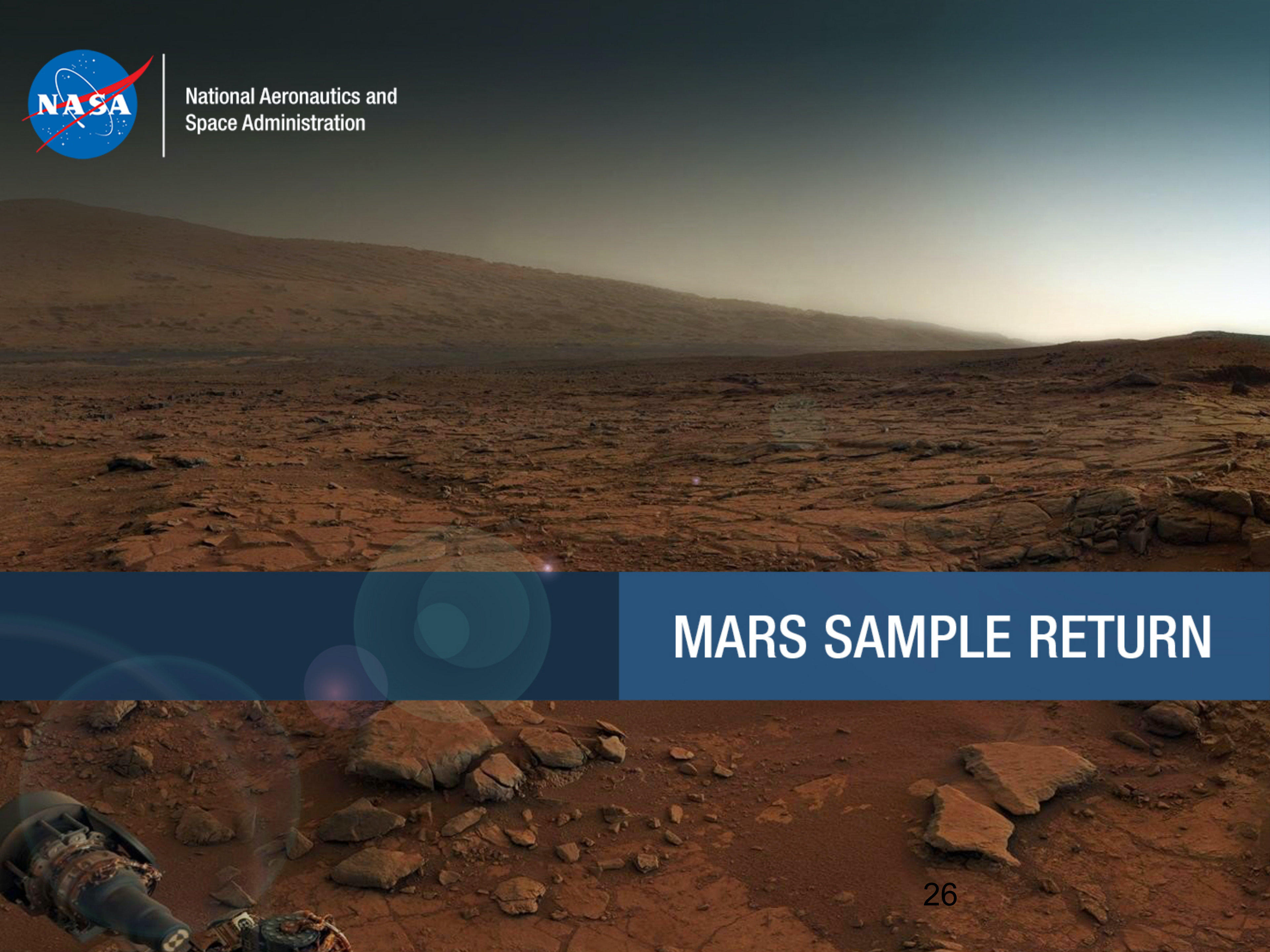
- Both Chemical and SEP propulsion options can meet MSR orbit matching needs for OS Rendezvous
  - Note: SEP case corresponds to high-acceleration SEP configuration, consistent with a fast-return MSR orbiter optimized for speed
- Key trade is between time-to-complete vs. propellant mass
  - SEP takes longer, but has a significantly lower propellant cost than Chemical



Conclusion

- Extensive MAV trade studies have established a Hybrid Propulsion, Single-Stage-to-Orbit MAV reference design for potential MSR
  - JPL/MSFC team working with industry partners to fully mature MAV technology to TRL 6 by 2022
- The Orbiting Sample (OS) – the physical interface between MAV and SRO – has a mature conceptual design
  - Fully incorporates M2020 sample tube design
- The SRO-OS Rendezvous function is well understood
  - Simple passive-imaging sensor suite is fully capable of supporting OS detection, approach, and terminal rendezvous phases

Key MSR technologies are on track to support SRL/SRO launch as early as 2026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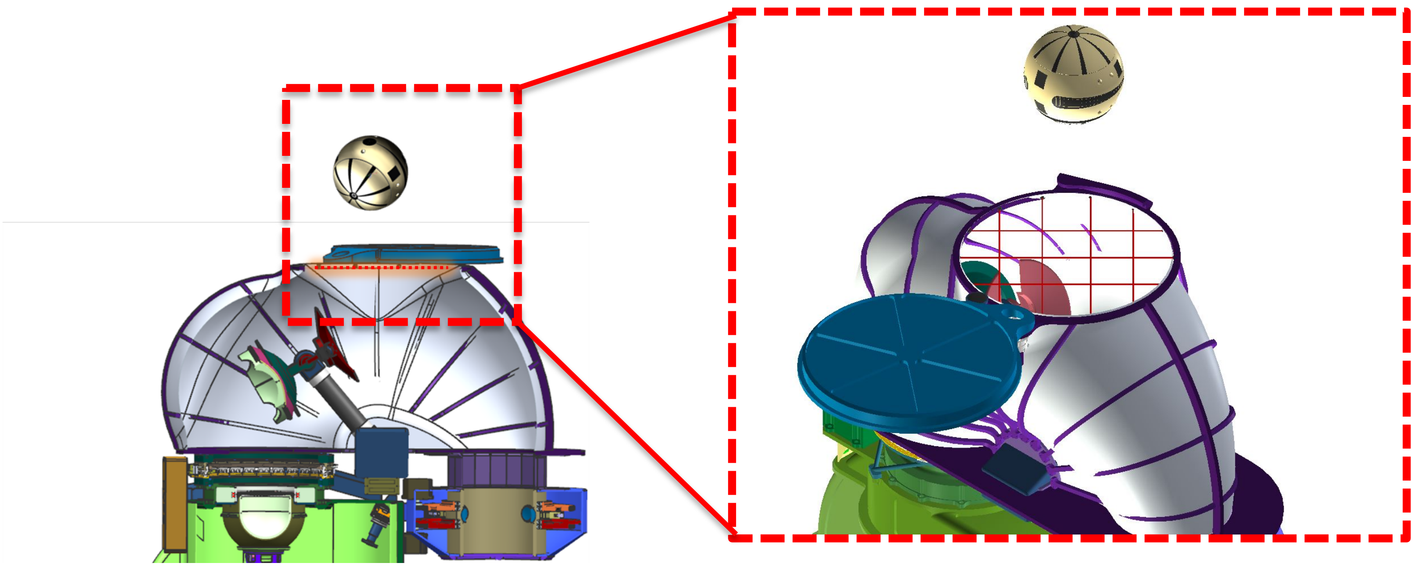
Space Administration
MARS SAMPLE RETURN

Backup

Capture Technology Development

OS Capture Concept Overview

- Function: Capture the OS in Mars orbit
- Multiple capture technologies have been successfully demonstrated
  - Bladed Capture
  - Capture Arm
  - Flux Pinning
- ROCS Capture Lid reference concept provides
  - Containment of OS and dust
  - Eliminates the need to simulate contact dynamics for V&V analysis and testing
  - Protects containment hardware from OS during capture
- Plan for TRL 4 end-to-end prototype demonstration in FY18

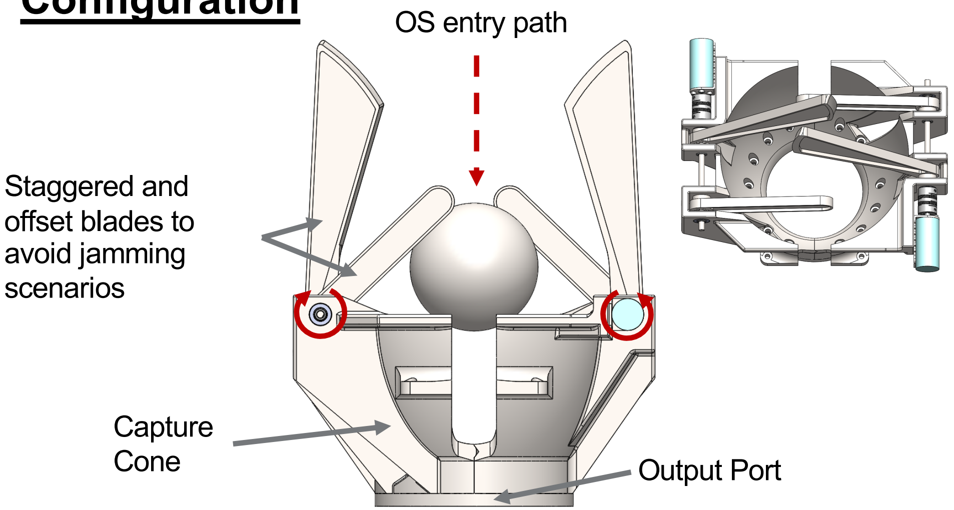


Bladed Capture Concept

Concept Overview

- Twin sets of blades rotate inward to cage the OS before it fully enters the Capture Cone
- Additional blade rotation guides the OS into the Capture Cone

Configuration



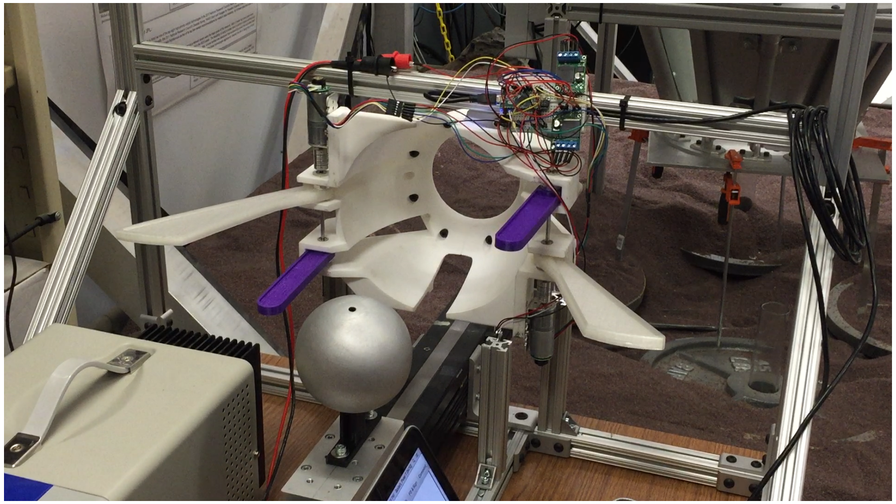
Evaluation

Pros:

- Large capture volume relative to stowed volume
- Small rotation (~30 degrees) required to cage the OS
- Single-fault tolerant
- Fully constrains the OS translation and can insert the OS into next subsystem

Cons:

- Does not control debris propagation

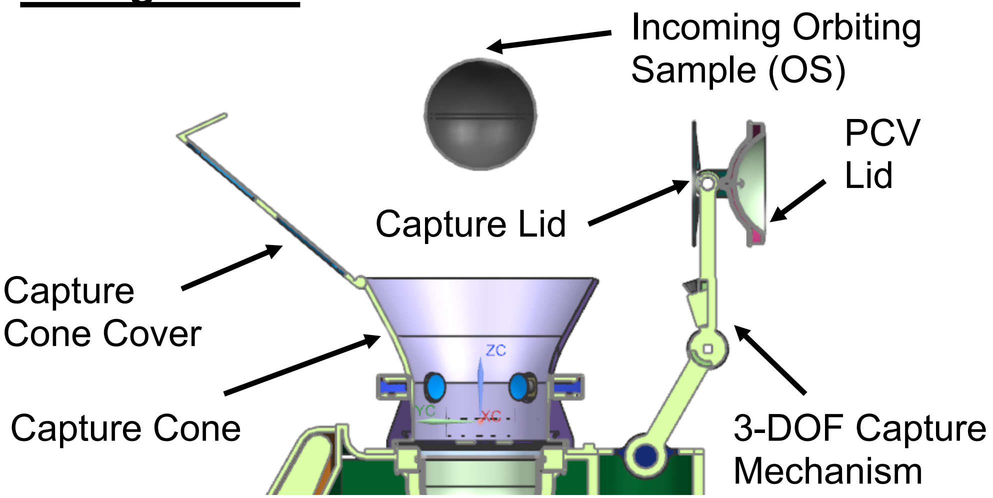


Capture Arm Concept

Concept Overview

- 3-DOF Capture Mechanism cages the OS in Capture Cone
- Further motions feeds the OS into the Capture Cone
- Capture Mechanism can provide a linear motion for containment vessel assembly around the OS

Configuration



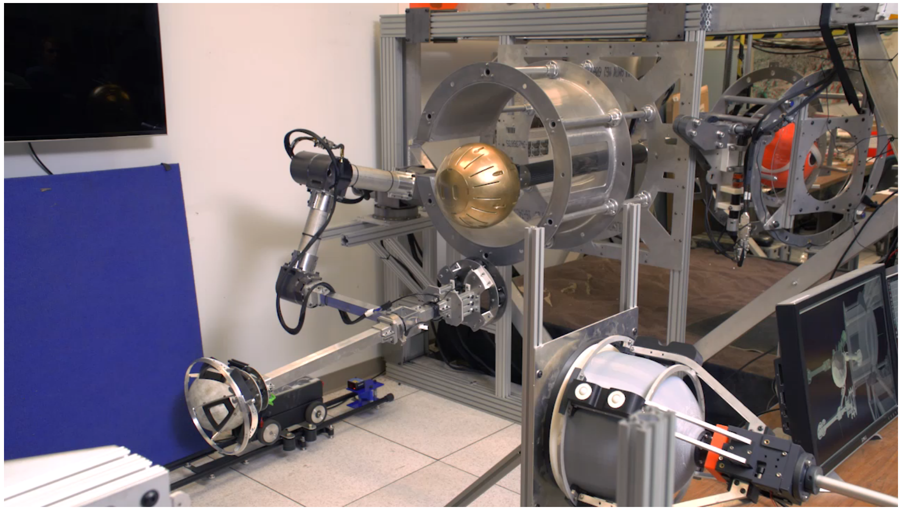
Evaluation

Pros:

- Large workspace
- Provides linear motion for containment vessel assembly

Cons:

- Higher actuator count
- More complex motor control

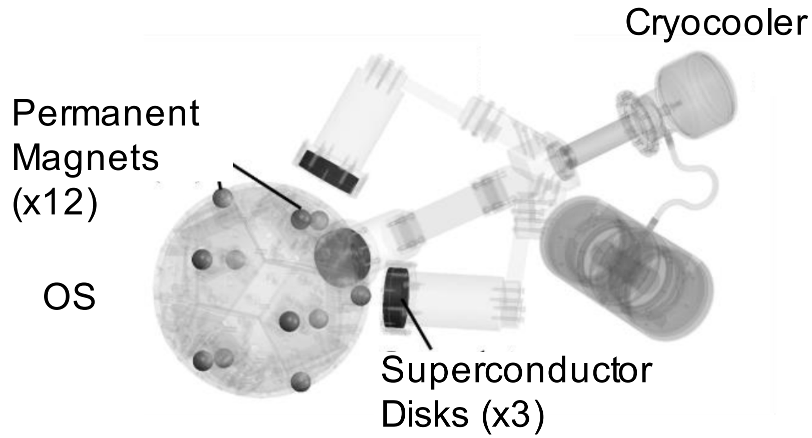


Flux Pinning Concept

Concept Overview

- Type-II superconductors are cooled below -185°C, during which magnetic flux lines can be "pinned" within the superconductor at a fixed position and orientation
- OS populated with surface permanent magnets can be captured by the cooled superconductors via flux pinning

Configuration



Evaluation

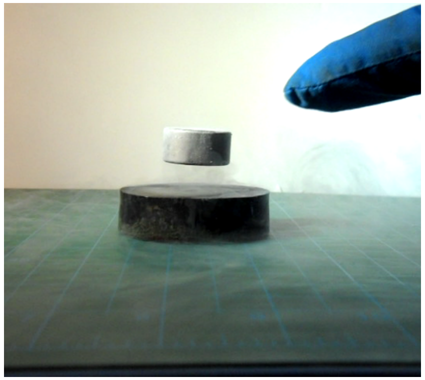
Pros:

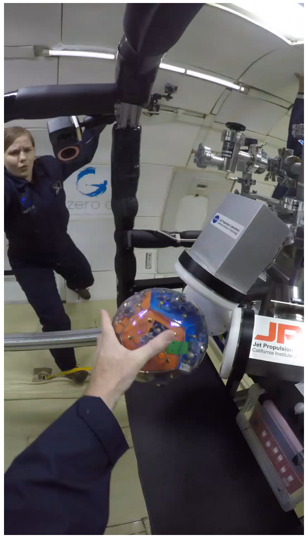
- Deterministic
- No mechanisms
- Mechanical interaction with the OS
- Can also provide orientation

Cons:

- Requires magnetic shielding in the OS to protect the samples
- Requires cryocoolers
- Limited 1 G testability

CONOPS:

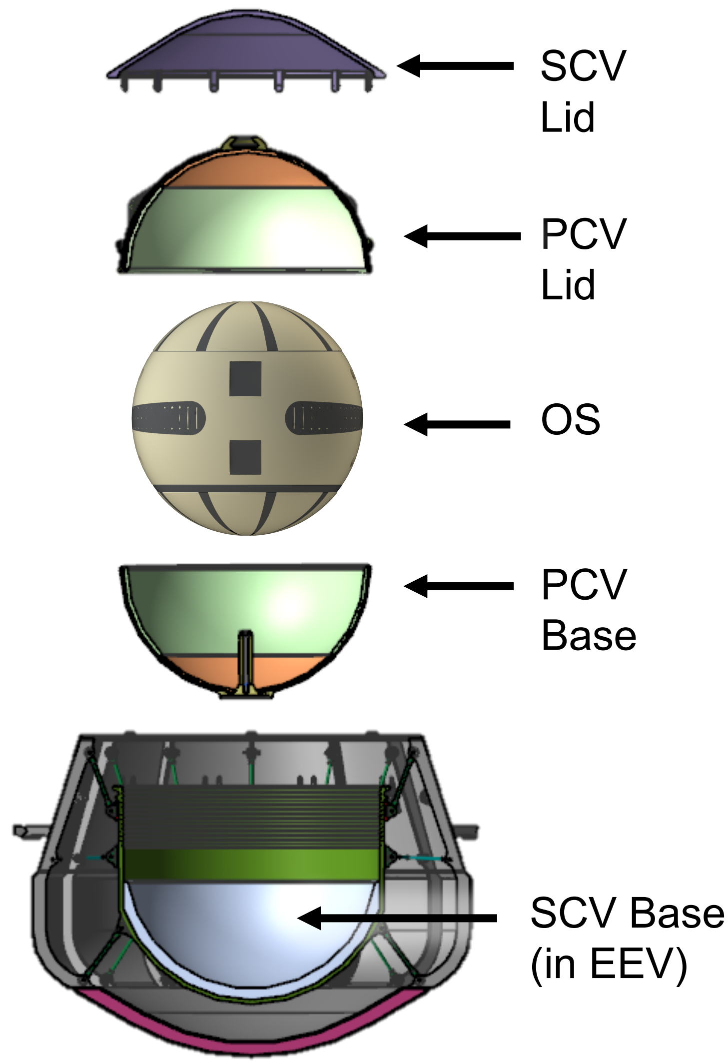




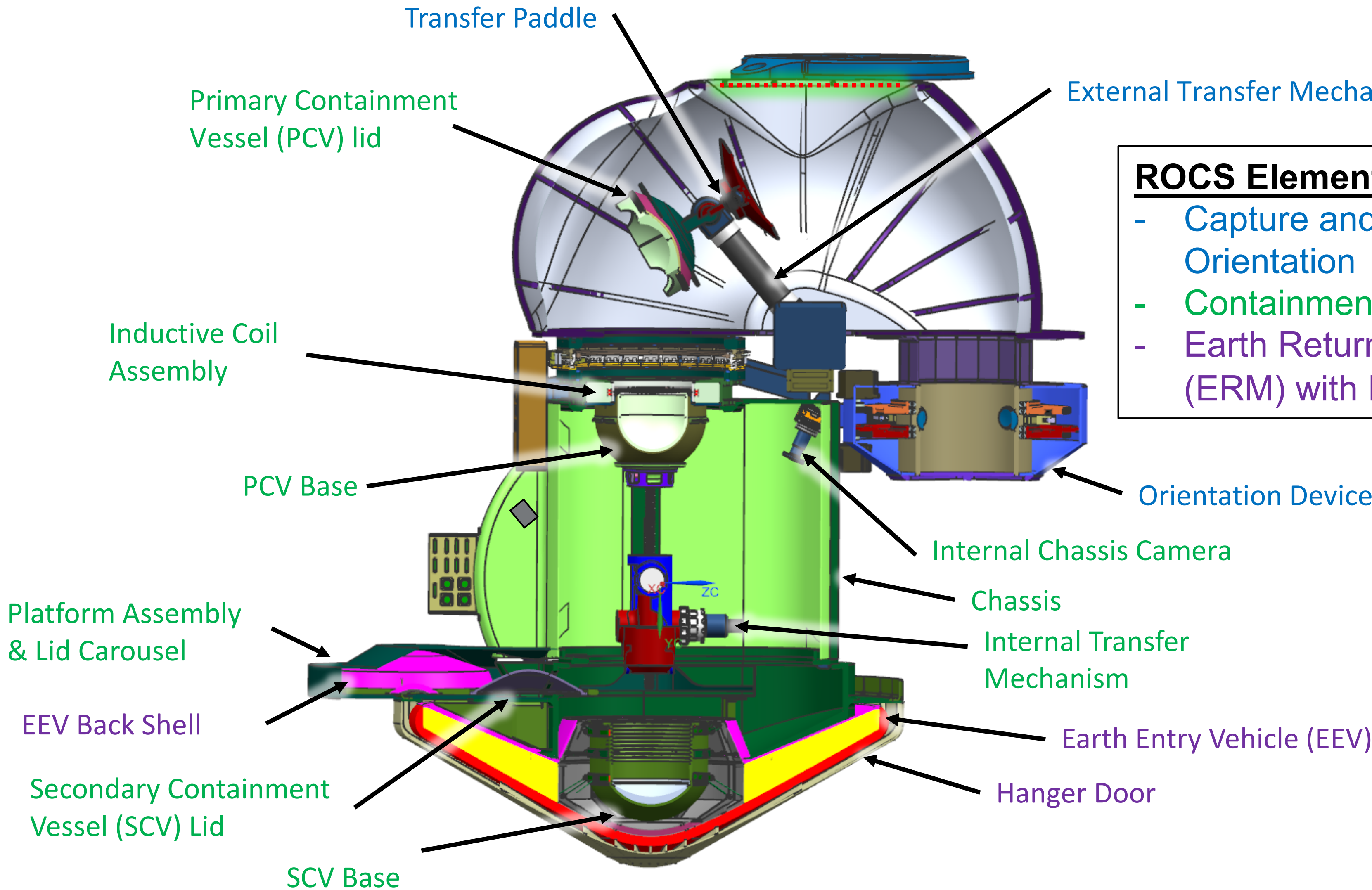
Bio-containment Technology Development

Biocontainment Concept Overview

- Biosealing comprises sub-elements of the Rendezvous and OS Capture System (ROCS):
  - Breaking-the-chain of contact with Mars (BTC)
  - Sealing a primary containment vessel (PCV)
  - Sealing a redundant secondary containment vessel (SCV)
  - Transferring the Contained-OS to the EEV (ERC)
- Studied several options and are focusing on a brazing system for simultaneous BTC and PCV sealing
- An o-ring or melt seal is used for SCV sealing
- Brazing system technology development (currently at quarter scale) is showing reliable results



ROCS Containment System Concept

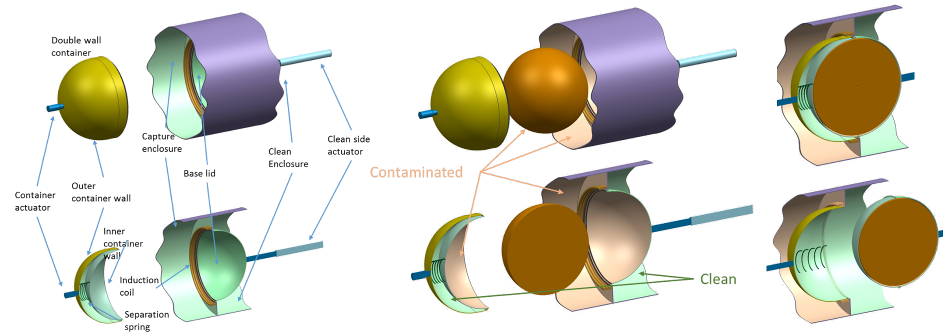


ROCS Elements

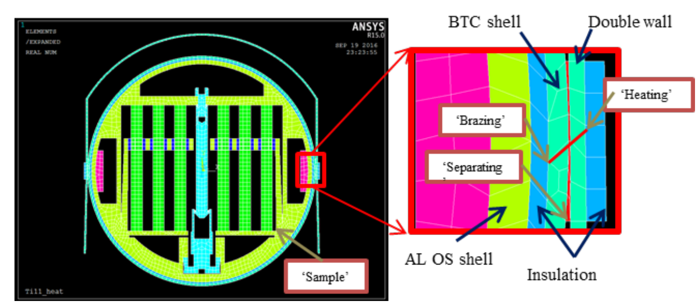
- Capture and Orientation
- Containment
- Earth Return Module (ERM) with EEV

Recent Technology Development

- Pursued multiple bio-containment technology candidates under Mars Program funding in FY14-17
  - Selected Brazing as primary BTC technology based on maturity and BTC performance
    - Key factor: assured sterilization
  - Continuing work on Bagging as alternate approach
  - Continue work on Plasma Sterilization as a potential supplement to BTC systems



Brazing Concept Overview



Finite Element Thermal Modeling of Braze Process

FY17 Quarter-Scale Brazing Tests

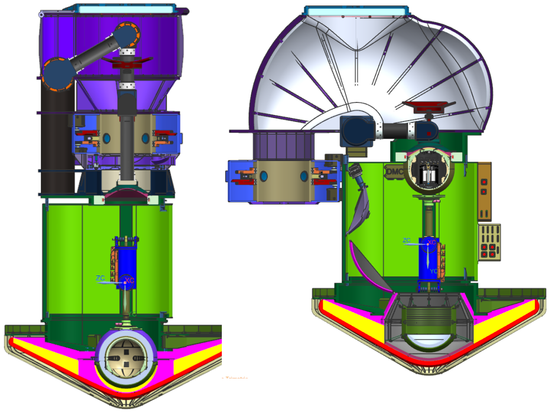
EEV Technology Development

Earth Entry Vehicle Concept Overview

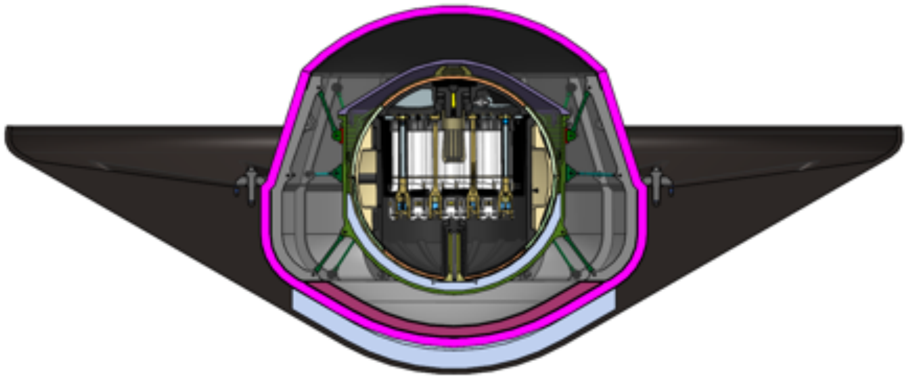
The Earth Entry Vehicle is a simple & reliable ballistic reentry vehicle for planetary sample return missions

1. No complex mechanisms
2. Stable aerodynamic shape from hypersonic thru sub-sonic
3. No parachutes
4. Redundant thermal protection systems
5. Multiple layers of energy absorbers
6. Robust & redundant containment vessels for planetary protection
7. 5-sigma landing ellipse fully within a controlled site

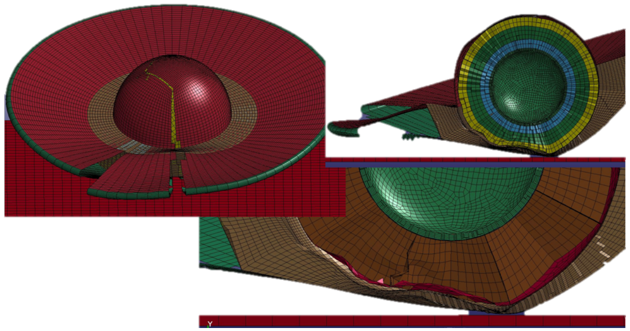
Different robotic assembly methods and EEV designs currently in trade



Current reference EEV concept



Advanced FEA used to characterize EEV behavior to nominal *and* off-nominal scenarios



Soft Soil Impact Testing

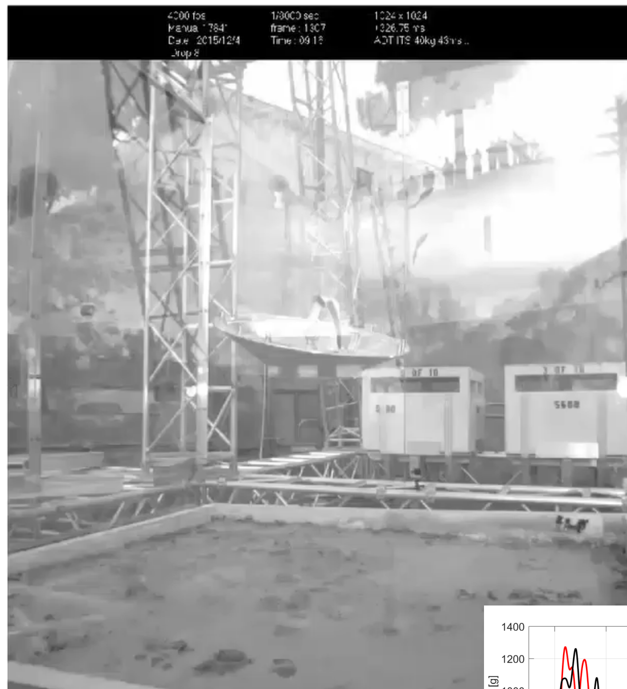
The 1300 G OS load requirement was validated with impact testing and analysis

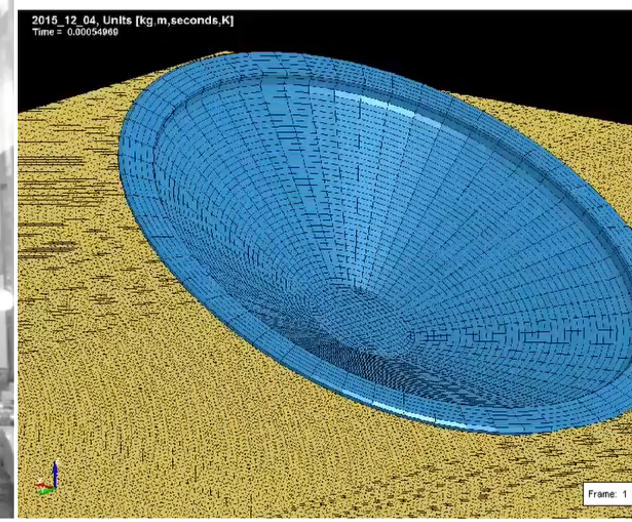
Impact tower constructed at JPL

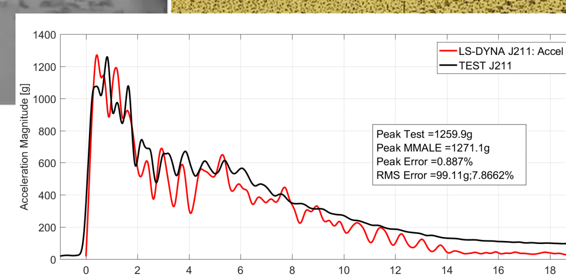
- 26 m tall truss – frame tower with pneumatic acceleration system
- 15 kg – 140 kg penetrometers tested at up to 140 kJ impact energy

FEM validated against 27x soft soil impact tests

Pen. I.D.	Mass [kg]	Orientation [°]	Vel. $\left[\frac{m}{s}\right]$	Energy [kJ]
SC-A	41.7	30	43.5	39.5





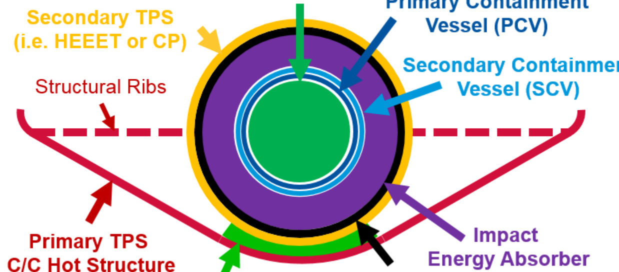


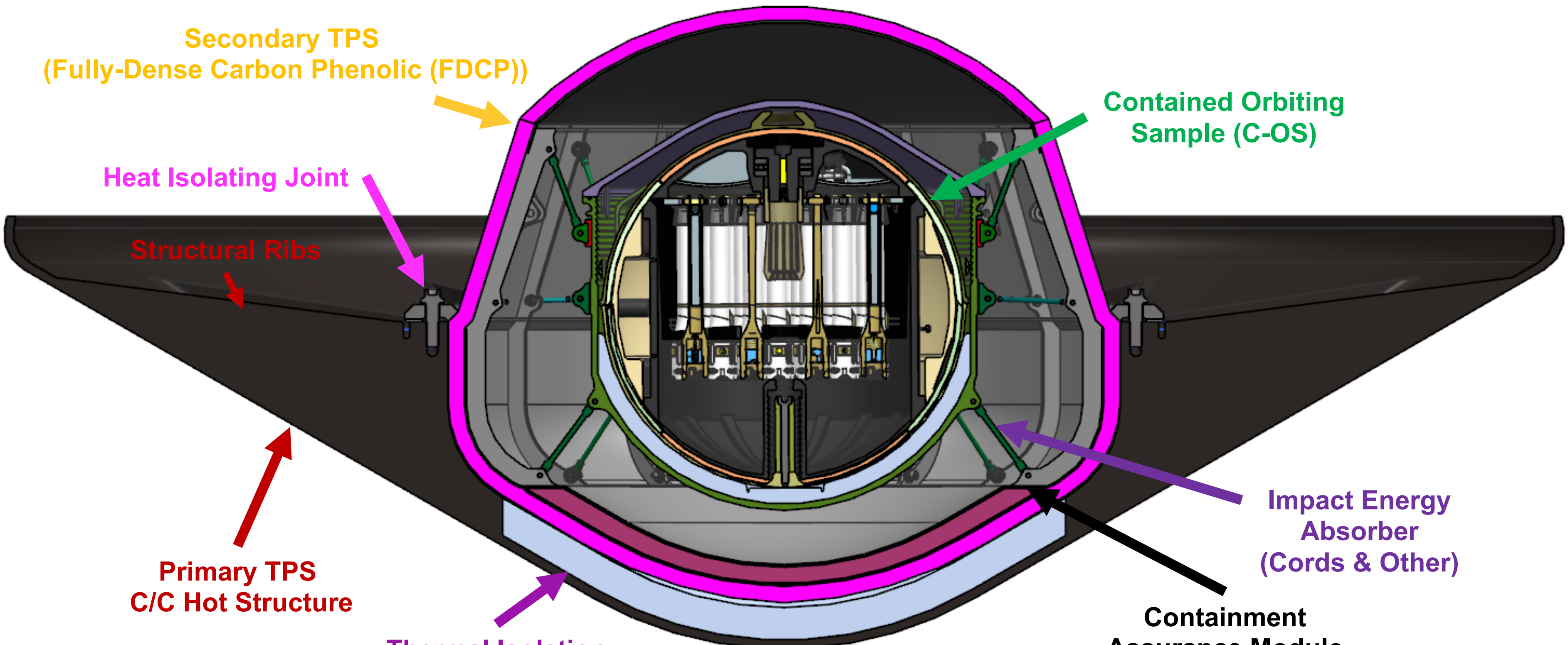
Accurate FE soil models validated via impact testing

Reference C/C EEV Concept

This concept is designed to address the containment assurance issues identified in the PRA

1) MMOD Risks, 2) Aerostability Risks, & 3) Landing Risks





Key Benefit: *All components outside of the CAM can withstand high heat, therefore 'TPS failure' i.e puncture of the C/C heat shield is unlikely to result in subsequent runaway failure modes.*